



Planck constraints on scalar-tensor cosmology and the variation of the gravitational constant

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Ooba *et al.* (2016)
arXiv:1602.00809 [astro-ph.CO].

Introduction

Extended theory

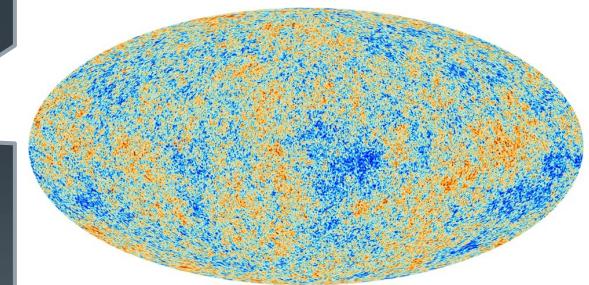
Modified gravity

Constraint

CMB

(cosmic microwave background)

scalar-tensor
 $f(R)$
Galileon
Horndeski
GLPV ...



PLANCK observation

The gravitational theory of our universe

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❖ Scalar-tensor theory (harmonic attractor model)

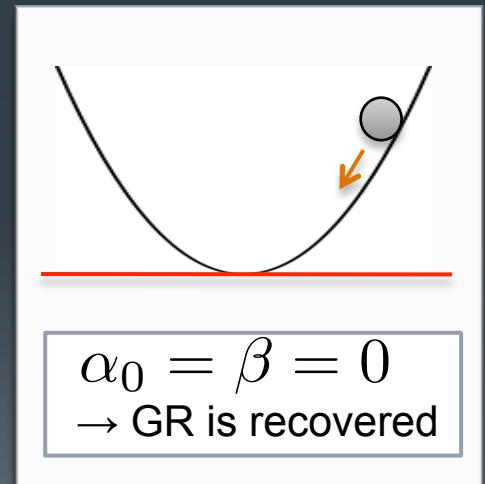
Action:

$$S = \frac{1}{16\pi G_0} \int d^4x \sqrt{-g} \left[\phi R - \frac{\omega(\phi)}{\phi} (\nabla\phi)^2 \right] + S_m$$

Coupling parameter:

$$2\omega(\phi) + 3 = \left\{ \alpha_0^2 - \beta \ln(\phi/\phi_0) \right\}^{-1}$$

- ϕ_0 : Today's scalar field value
- α_0, β : Today's potential gradient and curvature



❖ Background equations

Energy conservation:

$$\rho' + 3H(\rho + p) = 0$$

Friedmann eq:

$$H^2 = \frac{8\pi G_0}{3\phi} \rho a^2 - H \frac{\phi'}{\phi} + \frac{\omega}{6} \left(\frac{\phi'}{\phi} \right)^2$$

Scalar field EoM:

$$\phi'' + 2H\phi' = \frac{1}{2\omega + 3} \left\{ 8\pi G_0 a^2 (\rho - 3p) - \phi'^2 \frac{d\omega}{d\phi} \right\}$$

➤ $H \equiv \frac{a'}{a}$: Hubble parameter

➤ $(T^\mu_\nu) = \begin{pmatrix} -\rho & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix}$: Energy-momentum tensor

❖ Gravitational constant

The effective gravitational constant,
measured by “Cavendish-type” experiments:

$$G(\phi) = \frac{G_0}{\phi} \frac{2\omega(\phi) + 4}{2\omega(\phi) + 3} \propto \frac{1}{\phi}$$



To satisfy $G(\phi_0) = G_0$
(Using $2\omega(\phi) + 3 = \{\alpha_0^2 - \beta \ln(\phi/\phi_0)\}^{-1}$)

The present value of the scalar field:

$$\phi_0 = \frac{2\omega_0 + 4}{2\omega_0 + 3} = \frac{1 + \alpha_0^2}{\textcolor{red}{1 + \alpha_0^2}}$$

➤ The present deviation from the GR

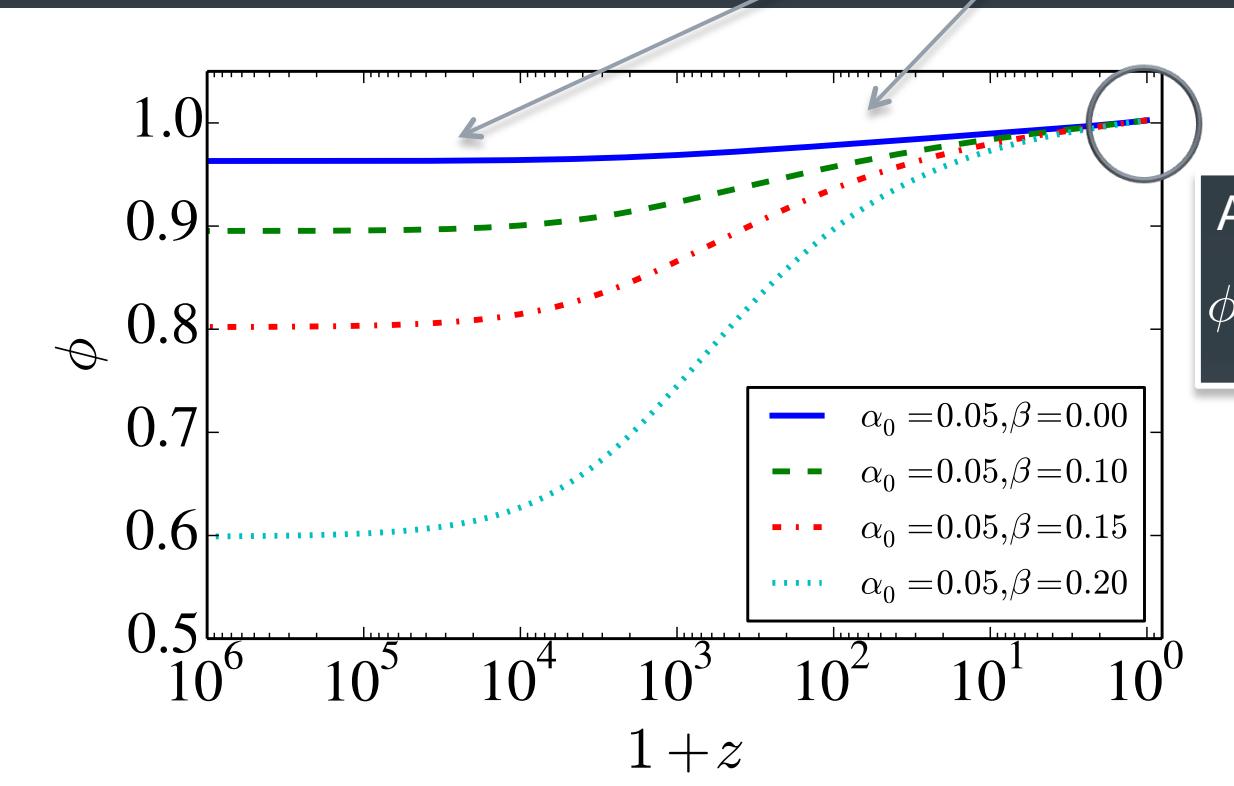
❖ Time variation of the scalar field

$$\phi'' + \left[2H\phi' + \frac{1}{2\omega+3}\phi'^2 \frac{d\omega}{d\phi} \right] = \frac{1}{2\omega+3} [8\pi G_0 a^2 (\rho - 3p)]$$

Friction term

➤ RD ($p_r = \rho_r/3$) := 0

➤ MD ($p_m \simeq 0$) : $\neq 0$



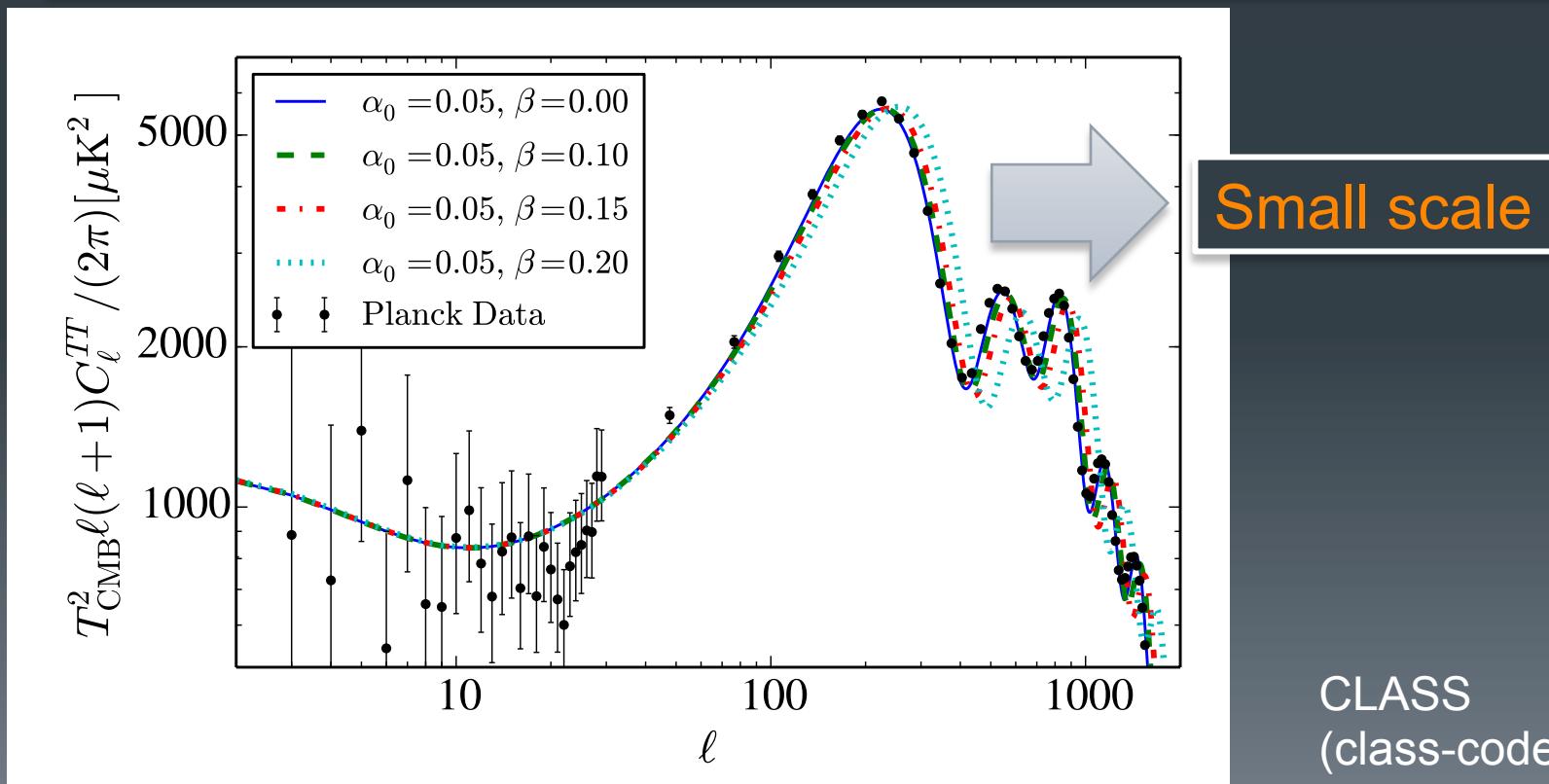
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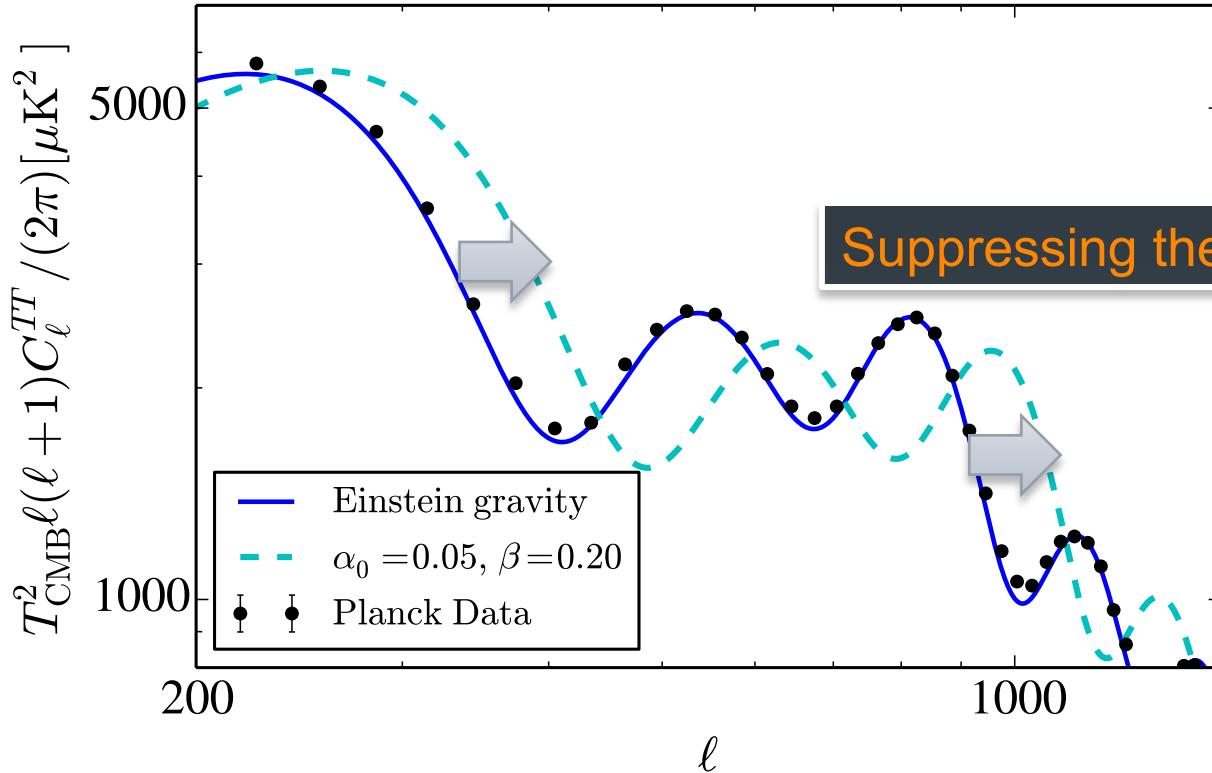
❖ The locations of the acoustic peaks

$$H^2 = \frac{8\pi G_0}{3\phi} \rho a^2 - H \frac{\phi'}{\phi} + \frac{\omega}{6} \left(\frac{\phi'}{\phi} \right)^2 \quad \left(\frac{\phi'}{\phi} \ll H \right)$$

- “ H ” is larger than its value under the GR in the early epoch.
- Hence a smaller horizon length at given redshift.



Damping



Suppressing the small scale peaks

- The peak scales ($\propto H^{-1}$), the damping scale ($\propto \sqrt{H^{-1}}$).
- Two scales become closer as “ H ” becomes larger.
- Hence the small scale peaks get stronger damping effect.

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❖ Method

Codes:

- CLASS (class-code.net)
To compute the fluctuations in the CMB.
- Monte Python (montepython.net)
To analyze data by using the Markov Chain Monte Carlo method.
(MCMC method)

Prior:

- In addition to the Λ CDM model parameters,
 $\alpha_0 \in (0, 0.5)$, $\beta \in (0, 0.4)$

Data:

- Planck 2015
Temperature and polarization anisotropies (TT , EE),
their cross-power spectrum (EE),
the lensing potential power spectrum.

❖ Result

Scalar-tensor coupling parameters:

$$\alpha_0^2 < 2.5 \times 10^{-4-4.5\beta} \text{ (95.45%)} \text{ (dashed black)}$$

$$\alpha_0^2 < 6.3 \times 10^{-4-4.5\beta} \text{ (99.99%)}$$

Using $2\omega(\phi) + 3 = \{\alpha_0^2 - \beta \ln(\phi/\phi_0)\}^{-1}$



$$\begin{aligned} \omega &> 2000 \text{ (95.45%)}, \omega > 1100 \text{ (99%)} \\ \omega &> 790 \text{ (99.99%)} \end{aligned}$$

Previous works:

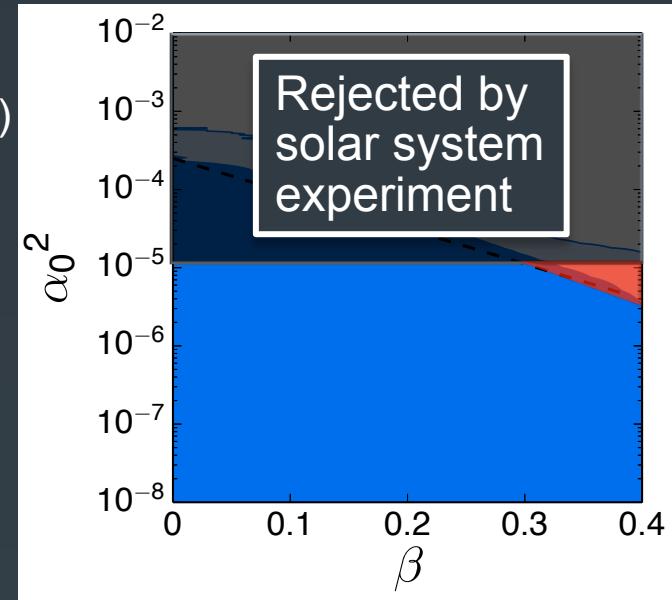
WMAP ➤ Nagata *et al.* (2004)

$\omega > 1000$ (50) at 2σ (4 σ)

Planck 2013 ➤ Avilez and Skordis (2014)

$\omega > 890$ at 99%

Solar System ➤ Bertotti *et al.* (2003), Will (2014) $\omega > 43000$ at 2σ (gray line)



In $\beta > 0.3$, our constraint is stronger than that determined in the Solar system study.

❖ Result

Time variation of the gravitational constant:

At the recombination epoch: $G_{\text{rec}} \equiv G(\phi_{\text{rec}})$

$$G_{\text{rec}}/G_0 < 1.0056 \text{ (95.45\%)}$$

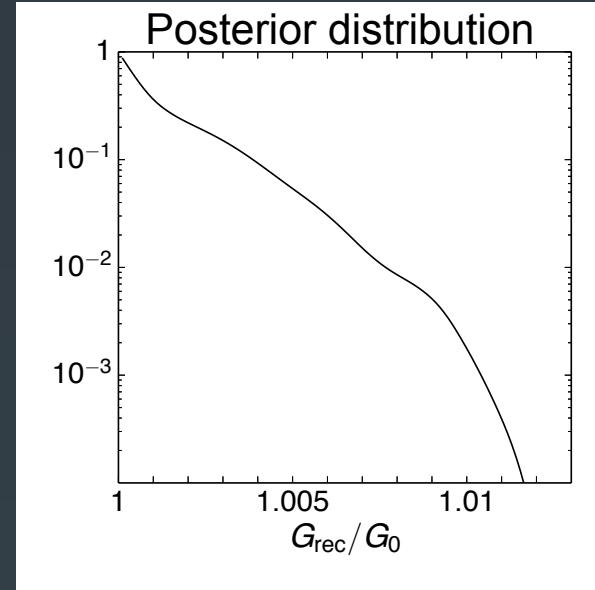
$$G_{\text{rec}}/G_0 < 1.0115 \text{ (99.99\%)}$$

The deviation from G_0 : < 1.15%

Previous works:

WMAP ➤ Nagata *et al.* (2004) $G_{\text{rec}}/G_0 < 1.23$ at (4σ) < 23%

Planck 2013 ➤ Li *et al.* (2013) $G_{\text{rec}}/G_0 < 1.029$ at (1σ) < 2.9%



➤ Our study places the strongest constraint
on the deviation of the gravitational constant.

❖ Result : including spatial curvature

- It also changes the acoustic peak scales of the CMB
(but not the damping scale)

Prior:

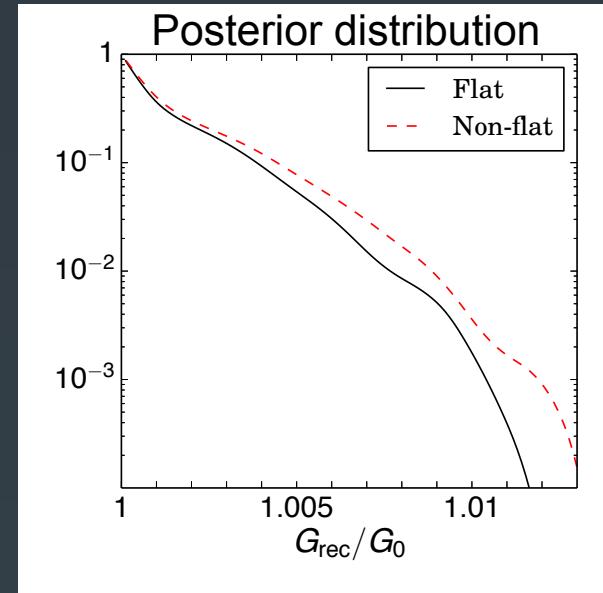
$$\Omega_K \in (-0.5, 0.5)$$

Nonflat universe case:

$$G_{\text{rec}}/G_0 < 1.0062 \text{ (95.45%)} \\ G_{\text{rec}}/G_0 < 1.0125 \text{ (99.99%)}$$

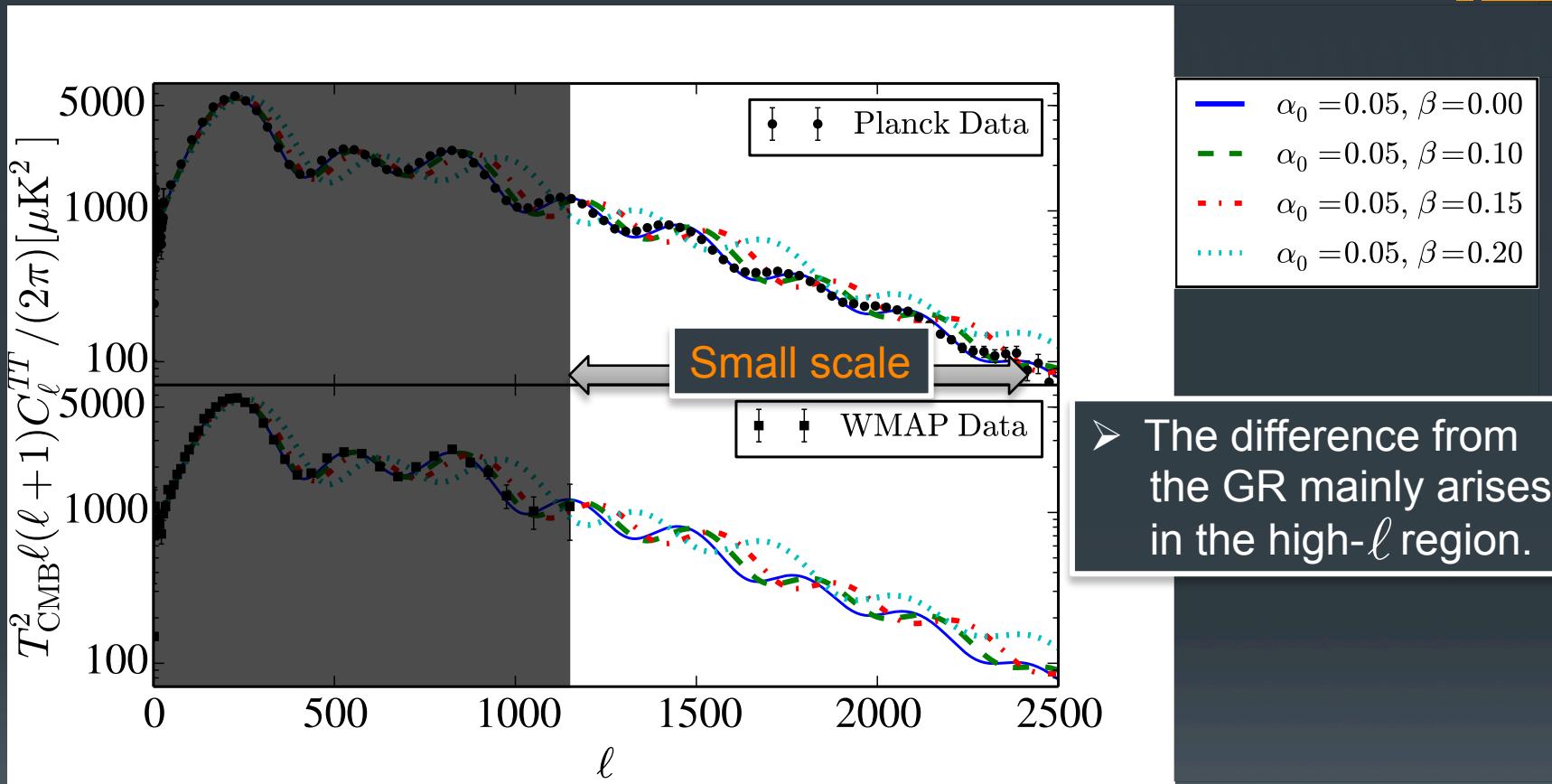
Flat universe case (same as previous slide):

$$G_{\text{rec}}/G_0 < 1.0056 \text{ (95.45%)} \\ G_{\text{rec}}/G_0 < 1.0115 \text{ (99.99%)}$$



- We have found that these constraints are fairly robust against the inclusion of spatial curvature.

❖ Planck vs. WMAP



- Therefore the constraints from the Planck data are much stronger than those from the WMAP data.
- Also the precise polarization spectra contribute to our result.

Summary

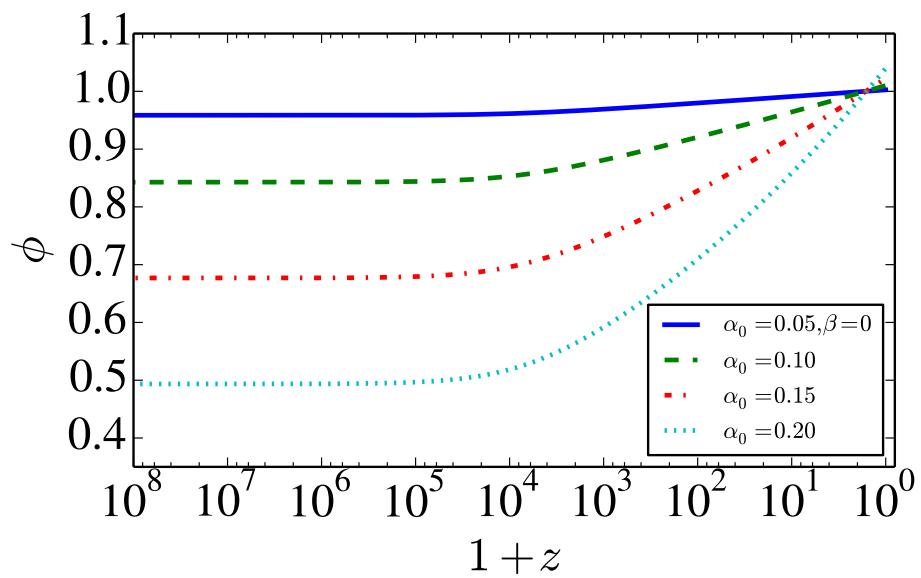
Ooba *et al.* (2016), Phys. Rev. D **93**, 122002

- We have constrained scalar-tensor Λ CDM model from the Planck data by using MCMC method.
- Our results are as follows.

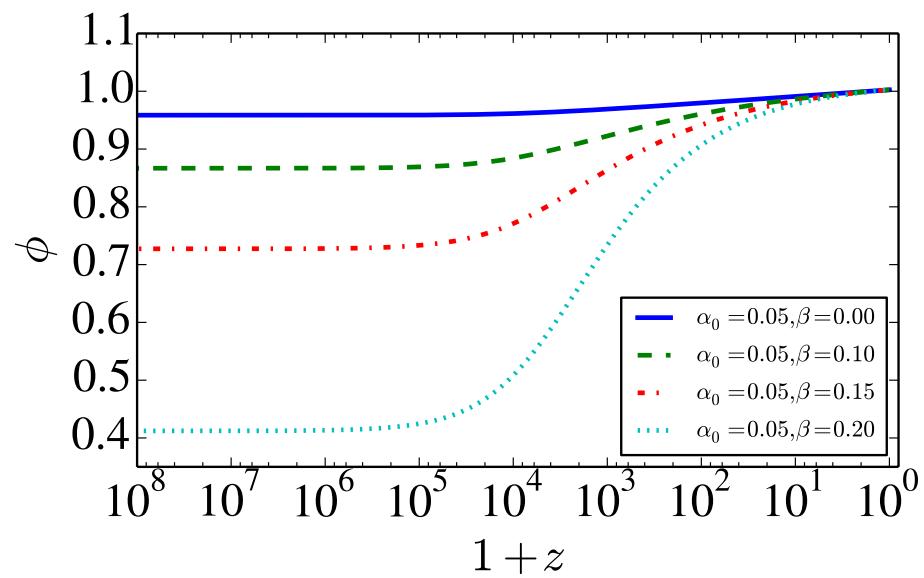
$\omega > 2000$ (95.45%)	$G_{\text{rec}}/G_0 < 1.0056$ (95.45%)
$\omega > 790$ (99.99%)	$G_{\text{rec}}/G_0 < 1.0115$ (99.99%)
- The significant improvement of these constraints is attributed to the precise measurements of the diffusion damping effect in the CMB power spectra.

Backup

Brans-Dicke

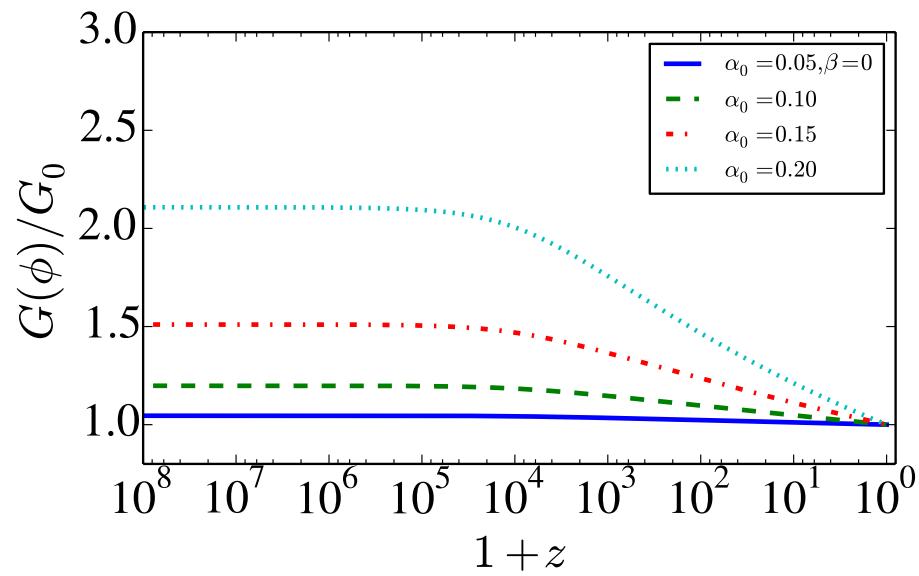


This work



Backup

Brans-Dicke



This work

